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Introducing Absolute Sustainable Lightweight Design

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Abstract

Absolute sustainability offers a promising approach for ensuring the needs of future generations continue to be met by setting sector and product-level sustainability targets based on the Earth's biophysical limits. In the context of sustainability, lightweight design is considered to have an ambiguous role when it comes to analyzing its environmental benefits: while it often promotes resource conservation in the use phase (e.g., minimizing energy consumption), it can also lead to shifting impacts to other life cycle stages (e.g., complicating recycling processes). Thus, combining lightweight design with absolute sustainability could help address these trade-offs.

Therefore, in this paper we introduce the concept and a definition of 'absolute sustainable lightweight design', where lightweighting reinforces positive environmental impacts while only allowing negative impacts within Earth's biophysical limits. The concept is applied to five body-in-white (BIW) lightweight material concepts (conventional steel, high-strength steel, advanced high-strength steel, aluminum, and composite) for internal combustion engine vehicles in the U.S. passenger car fleet and three different sharing principles for allocating the safe operating space within the planetary boundary 'climate change'. The results indicate that none of the lightweight BIW concepts can be classified as absolutely sustainable. Achieving absolute sustainability will require activating additional sustainability levers beyond lightweighting measures for the respective use case.

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1. Introduction

Sustainability has emerged as a central focus in global discussions, research, and policy development across diverse fields. The widely accepted definition of sustainability, as articulated by the Brundtland Commission [1], describes it as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." While this definition offers flexibility in interpreting what constitutes these *needs* and *how they are met*, the concept is often operationalized through the triple bottom line, conscientiously balancing the environmental, social, and economic pillars of sustainability [2]. However, a significant challenge arises when economic growth is used as a trade-off for environmental or social expenses [3].

In response to this limitation, the concept of absolute sustainability has gained prominence in recent years. This approach offers a more concrete framework by grounding sustainability within the Earth's planetary boundaries (PBs), which delineate the biophysical limits human activities must respect to prevent destabilizing ecosystems. Absolute sustainability thus introduces a top-down approach, where economic and social objectives can only be pursued if they remain within these environmental constraints encouraging the adoption of a life cycle engineering [4].

Within this context, lightweight design has regained significance as a strategy for enhancing resource efficiency (in terms of material use or energy consumption) of products and systems, alongside circular economy principles. Research in life cycle engineering of lightweighting measures consistently emphasizes that advanced lightweighting solutions are

particularly advantageous for applications involving products with energy-intensive use phases, even if they result in higher production or end-of-life impacts [5].

However, there has been no research to date examining whether these measures can be considered as aligned with the concept of absolute sustainability. Therefore, by integrating the principles of absolute sustainability with lightweight design, this approach has the potential not only to make products relatively ‘environmentally less bad’ but also to reveal trade-offs with other sustainability strategies (such as design for circularity) and to classify them as truly sustainable with respect to the Earth’s carrying capacity. Given this perspective, we address the following research question within this paper: *‘How can the engineering paradigm of lightweight design be combined with the concept of absolute sustainability and applied to product development?’*

To address the research question, the term *‘absolute sustainable lightweight design’* is first defined in Section 2 based on theoretical considerations and then integrated into a case study in Section 3. The case study covers the analysis of five different lightweight material concepts for the BIW in view of three sharing principles for downscaling the safe operating space (SOS), partly based on human needs. In Section 4, the present work is concluded and an outlook on future work provided.

2. Coupling Lightweight Design and Absolute Sustainability

2.1. Lightweight Design and Sustainability

Lightweight design in product development is typically divided into four fields of action [6–8]: conceptual, form, material, and manufacturing lightweight design, each representing different approaches to achieving the goal of weight reduction in products or systems. To establish a common understanding, we refer to the definition provided by König and Vielhaber [9] for the term ‘lightweight design’:

“Lightweight design is an engineering paradigm employing the weight reduction of technical systems as the means to realize one or more overarching development objectives while meeting various boundary conditions.”

While other definitions may also be considered, they generally differ only in the level of detail provided compared to the one presented. Typical motivators for applying lightweight design cover enabling or enhancing technical functionality, reducing life cycle costs or improving environmental performance [5].

The implementation of lightweight design measures from a sustainability perspective typically focuses on goals such as lowered material consumption, energy reduction, and emission savings, which are aligned with environmental sustainability objectives. Additional aspects can be found in [10].

However, while lightweight design can contribute to a product’s sustainability performance by reducing material

usage and improving energy efficiency delivering a high amount of technical functionality, there are also challenges discussed [5,11,12]. In particular, conflicts arise from increased material complexity (requiring more effort in raw material extraction and part production) and end-of-life challenges due to complex material designs requiring destructive disassembly methods. For instance, materials used in lightweight structures, such as composites, can complicate recycling processes or lead to higher environmental impacts during manufacturing. Therefore, the relationship between lightweight design and sustainability requires careful evaluation, particularly when considering the entire product life cycle.

2.2. Absolute Environmental Sustainability in Manufacturing Systems

The concept of absolute sustainability is based on respecting the Earth’s carrying capacity and fulfilling human needs in a derived SOS, delimited by a total of nine critical environmental thresholds, known as the PBs [13]. These boundaries define the biophysical limits within which humanity can meet its needs without compromising the stability of the Earth’s ecosystems [14,15]. Hauschild and Bjørn [16] have further developed this societal concept for individual products by proposing an assessment methodology that allocates PBs to sectors, industries, and, ultimately, individual products. Therefore, a top-down allocation approach is central to absolute sustainability. It ensures that economic and social objectives are pursued only within the confines of these planetary limits. For a shared understanding, the CIRP scientific community [17] defines:

Absolute sustainability means “meeting the needs of present and future generations while staying within the planet’s biophysical limits. They should be seen as absolute constraints. Sustainability trade-offs between environmental, societal and economic objectives can only occur as long as we ensure that our activity does not impact the environment beyond its operating space within these limits.”

In this context, this study will focus solely on the environmental dimension of sustainability, emphasizing life cycle engineering. This approach prevents positive social or economic effects from being used to justify environmentally harmful actions [4].

2.3. Defining ‘Absolute Sustainable Lightweight Design’

As observed by Hauschild [18] in relation to the general definition of sustainability from the Brundtland Report [1], the concept of absolute sustainability leaves room for interpretation, particularly regarding the *needs* of present and future generations. These needs are not concretely defined and remain flexible. Additionally, the *way these needs are met* is another flexible element, heavily influenced by factors outlined in the ‘IPAT equation’. Lightweight design, as an engineering

paradigm, focuses primarily on weight reduction for technical systems, which leads to the first challenge in merging the two definitions: while absolute sustainability addresses the fulfillment of humanity's needs (operating within society) while respecting the carrying capacity, lightweight design aims to support the optimization of technical systems. Fundamentally, lightweight design could be one possibility for the way to meet needs of the present and the future within absolute sustainability.

Having this background in mind and given the definition of lightweight design, there are two possible approaches for integrating absolute sustainability into the development of lightweight products. First, the objective behind weight reduction could vary. The literature frequently mentions functional improvements, costs, or resource conservation (eco-efficiency) as common goals of lightweight design. Thus, absolute sustainability could become the primary *objective* behind implementing a weight reduction. Defining absolute sustainability as a goal for lightweight design could be viewed as an intermediate step in demonstrating whether and how this integration is possible. We refer to this approach as '*lightweight design towards absolute sustainability*', providing the following definition:

'Lightweight design towards absolute sustainability is an engineering approach that employs weight reduction strategies to enhance resource efficiency and environmental performance while progressively aligning with the principles of absolute sustainability. It aims to minimize environmental impacts across the product life cycle, contributing to sustainability objectives, yet acknowledges the need for continuous improvement to remain within the planet's biophysical limits.'

This solution is less straightforward, as absolute sustainability defines Earth's biophysical limits as fixed boundaries. Therefore, a second option is represented by defining absolute sustainability as the *boundary condition* or *constraint* in the implementation of any weight reduction. In

this case, absolute sustainability would act as a clear limit for all lightweighting efforts. This approach leads to our proposed definition of '*absolute sustainable lightweight design*':

'Absolute sustainable lightweight design combines the principles of absolute sustainability and lightweight engineering, employing the weight reduction of technical systems to achieve overarching development goals, while ensuring that the weight reduction does not cause environmental impacts beyond the planet's biophysical limits, that have to be regarded as absolute constraints.'

This way, lightweight design becomes a design paradigm, where products or systems are optimized to maximize positive environmental impacts as well as the way human needs are met while ensuring that any negative environmental effects remain within Earth's carrying capacity.

3. Application Example: Absolute Sustainable Lightweight Body-in-White Vehicle Design

The following study should be understood as proof-of-concept. The objective of the case study in this paper is to methodologically demonstrate the idea of combining lightweight design with the concept of absolute sustainability to discuss our proposed definitions, illustrated using the 'absolute environmental sustainability assessment' (AESA) of five different automotive BIW lightweighting material concepts (conventional steel, high-strength steel, advanced high-strength steel, aluminum, and composite). It should be noted that the environmental benefits of implementing lightweight design can vary depending on the product's characteristics. Therefore, we have focused on an automotive component, as it has a significant impact due to the movement of mass during the vehicle's use phase.

In our calculations, several assumptions are made. We focus in our analysis of the BIW concepts on internal combustion engine vehicles (ICEVs) within the U.S. passenger car fleet. The evaluation of material selection concerning absolute

Table 1. Used data for the evaluation of all BIW lightweighting concepts and each of the three principles for determining the SoSOS.

Description	Abbreviation	Source	Year	Unit	Value
SOS for the PB 'climate change' per year	SOS _{CC}	[19]	2019	kg CO ₂ eq.	6.81e+12
United States population	POP _{USA}	[20]	2022	-	343,477,335
World population	POP _{GLO}	[21]	2022	-	8,021,407,192
Annual global GHG emissions	SQ _{CC} ^{GLO}	[22]	2022	Gt CO ₂ eq.	57.2
GHG emissions for road transportation per capita in USA	SQ _{CC} ^{USA,PC,CAR}	[23]	2018	kg CO ₂ eq.	4,486
Annual travelled distance with road transportation per capita in USA	d _{CAR} ^{USA,PC}	[24]	2022	km	15,992
Functional unit for vehicle usage scenario	d _{CAR}	[25]	2012	km	200,000
Number of registered vehicles in USA	n _{CAR} ^{USA}	[26]	2022	-	283,400,986
Number of registered internal combustion engine vehicles in USA	n _{ICE} ^{USA}	[27]	2022	-	241,372,900
Share of FCE on road transportation in USA	SoFCE _{CAR} ^{USA}	[28]	2022	%	12.5
FCE (global)	FCE ^{GLO}	[29]	2022	\$	7.265e+13
FCE (USA)	FCE ^{USA}	[29]	2022	\$	2.108e+13

Table 2. Differences in the used reference data determining the SoSOS for the five different BIW lightweight material designs.

Description	Abbrev.	Source	Year	Unit	Steel	HSS	AHSS	Al	Composite
Life cycle GHG emissions per kg BIW	SQ_{LC}^{BIW}	[25]	2012	kg CO2 eq / kg BIW	65.667	65.752	66.089	64.176	76.547
BIW weight	m^{BIW}	[25]	2012	kg	270	240	203	135	123
Curb weight	m^{CAR}	Estimated from [25,32]	2012, 2022	kg	1,570	1,540	1,503	1,435	1,423
Life cycle GHG emissions for vehicles per km	$SQ_{LC,km}^{CAR}$	Calculated from [32]	2022	g CO2 eq / km	215.000	207.941	199.235	183.235	180.412
Share of total life cycle GHG emissions from BIW for vehicle	$SoSQ_{CAR}^{BIW}$	Calculated from indicated values	-	%	41.24	37.94	33.67	36.65	36.08
Life cycle costs of BIW	LCC^{BIW}	Calculated from [33]	2022	€	4,825,93	5,412.92	3,660.87	3,368.77	10,867.52
Life cycle costs of vehicle	LCC^{CAR}	Calculated from [33]	2022	€	74,147.00	74,733.99	72,981.93	71,436.45	80,188.59

sustainability is conducted for the entire fleet as of 2022, as more recent data is largely unavailable. We calculate the environmental performance of the BIW concepts under the hypothetical scenario that all ICEV are equipped with the respective material concept. Therefore, we define the functional unit as ‘providing structural stability for all U.S. personal light-duty vehicles with a total mileage of 200,000 km’. The quantification and subsequent evaluation of environmental impacts is based on life cycle assessment (LCA) data, as summarized in Bjørn et al.’s review as ‘LCA-based AESA’ [30]. Our calculations are based upon the LCA of lightweight material BIW concepts by Mayyas et al. (2012) [31].

The system boundary and assumptions for our evaluation of the BIW concepts align with the system boundary of the original reference LCA. Moreover, our analysis primarily relies on data from other scientific sources, as outlined in the following subsection, particularly for determining the downscaled share of the safe operating space (SoSOS). For transparency, we have provided detailed references for all data and sources used. Any simplifications made in the original sources apply equally to this evaluation. Additionally, further simplifications were made due to data limitations, which are explained in the subsequent sections.

3.1. Assigning the Share of the Safe Operating Space

We use as sharing principle for determining the SoSOS only in the PB ‘climate change’ (CC) to the product (in our case: lightweight BIW concepts implemented by five different material compositions) the principle ‘fulfillment of human needs’ (FHN) proposed by Heide et al. (2023) [34]. The FHN principle is a combination of different established sharing principles. Thereby, first the ‘egalitarianism’ principle is used, wherein the SOS is downscaled within the PB CC using ‘equal per capita’ (EPC) sharing. Secondly, the status quo (SQ) principle gets applied, wherein it is apprehended that sectors demand varying shares of the PB. The SQ principle belongs to the acquired rights distributive justice theory and is similar to the grandfathering principle but uses current emissions instead of historical emissions. This is complemented by additional

principles that calculate the importance of a population’s needs based on the final consumption expenditure (FCE) in a sector.

All data used for the calculations, a short description and their corresponding sources are presented in Table 1 for shared data regarding all BIW lightweight material concepts and in Table 2 for separate data for each of the different concepts. The impacts in the PB CC are calculated based on life cycle greenhouse gas (GHG) emissions as they represent one of the main contributors to the environmental footprint and the global warming potential. It has also been chosen because of data availability reasons.

For the SQ calculation, we took an EPC share of the global SQ GHG emissions (Q_{CC}^{GLO}) and scaled it up for the ‘road transportation’ sector to the entire population of the USA ($POP_{USA} \cdot SQ_{CC}^{USA,PC,CAR}$). The resulting amount is proportionally adjusted for the system boundary under consideration (only ICEVs ($n_{ICE}^{USA} / n_{CAR}^{USA}$)) and only considering the share of the BIW to the mass-dependent life cycle GHG emissions of an ICEV. For determining this, we have followed the evaluations of Buberger et al. (2022) [32]. According to the following equation (1), we thus obtain the SoSOS for each of the five BIW concepts within the PB CC for the year t (in our case 2022) when inserting the values from Table 1 and 2 considering the provided units:

$$SoSOS_{CC,BIW}^{SQ}(t) = SOS_{CC} \cdot \frac{POP_{USA} \cdot SQ_{CC}^{USA,PC,CAR}}{SQ_{CC}^{GLO}} \cdot \frac{n_{ICE}^{USA}}{n_{CAR}^{USA}} \cdot SoSQ_{CAR}^{BIW} \tag{1}$$

Secondly, we performed an evaluation of the BIW concepts regarding absolute environmental sustainability based on the FCE of the U.S. population for road transportation according to equation (2). Therein the SoSOS for the BIW is calculated on the SQ of current consumption patterns of the U.S. inhabitants to road transportation (an average of 12.5% is typically spent in relation to their income [28]), $SoFCE_{CAR}^{USA}$ in a relative comparison to the SQ of FCE from the USA to global consumptions patterns ($FCE_{CC}^{USA} / FCE_{CC}^{GLO}$). The resulting SoSOS is proportionally calculated for the number of ICEVs to the total number of registered vehicles ($n_{ICEV}^{USA} / n_{CAR}^{USA}$) as well as the life cycle costs (LCC) from the BIW as part of the LCC of an entire vehicle (LCC^{BIW} / LCC^{CAR}) within our defined functional unit of 200,000 km driving range.

Table 3. Results of the case study.

Description	Abbrev.	Unit	Steel	HSS	AHSS	Al	Composite
Status quo LCA for the BIW in the USA per year	LCA_{BIW}^{USA}	kg CO2 eq	3.40e+11	3.03e+11	2.57e+11	1.66e+11	1.81e+11
SQ calculated CC SoSOS for the BIW in the USA per year	$SoSOS_{CC,BIW}^{SQ}$	kg CO2 eq	6.44e+10	5.93e+10	5.26e+10	3.69e+10	4.08e+10
SQ sustainability ratio	SR_{SQ}	-	5.28	5.11	4.89	4.50	4.43
FCE calculated CC SoSOS for the BIW in the USA per year	$SoSOS_{CC,BIW}^{FCE}$	kg CO2 eq	1.75e+10	1.95e+10	1.35e+10	1.25e+10	3.66e+10
FCE sustainability ratio	SR_{FCE}	-	19.41	15.52	19.06	13.32	4.95
SQ + FCE calculated CC SoSOS for the BIW in the USA per year	$SoSOS_{CC,BIW}^{SQ+FCE}$	kg CO2 eq	7.51e+8	8.35e+8	5.78e+8	5.34e+8	1.56e+9
SQ + FCE sustainability ratio	SR_{SQ+FCE}	-	453.37	362.55	445.06	311.08	115.60

$$SoSOS_{CC,BIW}^{FCE}(t) = SoS_{CC} \cdot SoFCE_{CAR}^{USA} \cdot \frac{FCE_{CAR}^{USA}}{FCE_{GLO}} \cdot \frac{LCC_{CAR}^{BIW}}{LCC_{CAR}} \cdot \frac{n_{ICEV}^{USA}}{n_{CAR}^{USA}} \quad (2)$$

$$LCA_{BIW}^{USA} = m^{BIW} \cdot SQ_{LC}^{BIW} \cdot n_{ICEV}^{USA} \cdot \frac{d_{CAR}^{USA,PC}}{d_{CAR}} \quad (4)$$

Lastly, we mixed both principles by using an EPC share for the U.S. population (POP^{USA} / POP^{GLO}) instead of an FCE based assignment for the first downscaling the SOS to the country. Within the USA, the FCE based determination of their needs as method to assign the SoSOS for the USA to the road transportation sector ($SoFCE_{CAR}^{USA}$) is performed according to equation 3.

$$SoSOS_{CC,BIW}^{SQ+FCE}(t) = SoS_{CC} \cdot \frac{POP^{USA}}{POP^{GLO}} \cdot SoFCE_{CAR}^{USA} \cdot \frac{LCC_{CAR}^{BIW}}{LCC_{CAR}} \cdot \frac{n_{ICEV}^{USA}}{n_{CAR}^{USA}} \quad (3)$$

To compare the impacts of each BIW lightweight material concept calculated using the presented sharing principles with the actual life cycle GHG emissions, a current LCA score was calculated based on the available data, in accordance to equation (4). This score evaluates the entire life cycle of a vehicle over a usage scenario of 200,000 km, based on the average annual distance traveled by each U.S. citizen, scaled to a reference year ($d_{CAR}^{USA,PC} / d_{CAR}$), which is in our case 2022, and all registered ICEVs. This LCA score, like all calculated SoSOS values for the BIW concepts, should be understood as representing the SQ of the PB CC for the entire U.S. population and all registered ICEVs of the road transportation sector. It represents the annual GWP that would occur under the current consumption pattern if all ICEVs were equipped with the respective BIW lightweight material concepts.

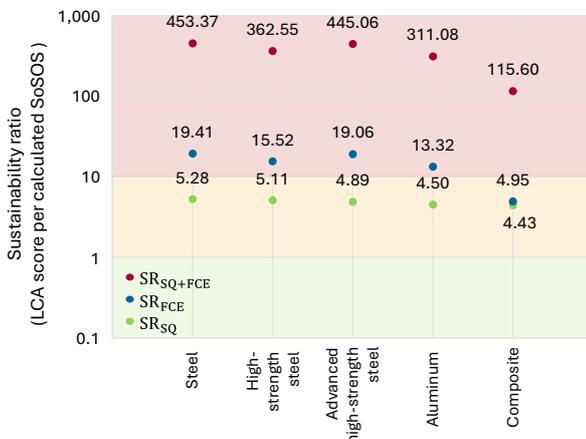


Fig. 1. Sustainability ratio of the five different lightweight BIW concepts for the U.S. road transportation sector based on three different sharing principles for determining the SoSOS.

The values calculated using the provided formulas, along with the relative sustainability ratio (SR, calculated as the division of the LCA score by the respective SoSOS for each sharing principle) are presented in Table 3. Additionally, Fig. 1 illustrates the determined relative SRs for each BIW concept and sharing principle on a logarithmic vertical axis.

3.2. Discussion of the Results

Examining the results in Table 3 and Fig. 1, it can be concluded that none of the five lightweight BIW concepts achieve a relative SR below 1 while only evaluating the environmental dimension of absolute sustainability. This indicates that none of these concepts can be considered as environmentally absolute sustainable, nor can they be classified as ‘absolute sustainable lightweight designs’ according to the definitions provided earlier. Depending on the sharing principle, the different material concepts for ICEVs (such as conventional steel) in the USA exceed the PB CC by a factor of over 450. The EPC distribution of the SoSOS, based on current GHG emissions (SQ results), generally yields the lowest values, while incorporating FCE on the road transportation sector leads to significantly higher values. These findings align with the results of Lavis et al. (2024) [35] for batteries in battery electric vehicles in the context of French private transport. Notably, in view of the FCE and SQ+FCE results, the composite-intensive BIW concept shows a SR only about a quarter of that of the conventional steel alternative. This outcome arises from the more costly BIW concepts depending on the higher lightweighting effort, which increases the accepted SoSOS based on the vehicle’s entire LCC.

However, it is important to emphasize that lightweight design for BIW vehicle components does offer an opportunity to make designs more sustainable, thus serving as a supportive measure in developing an absolutely sustainable product. Nevertheless, lightweighting the BIW alone cannot be the sole approach to enhancing the environmental sustainability of conventional ICEVs. As a result, our case study can be categorized under the proposed definition of ‘lightweight design towards absolute sustainability’.

To achieve classification as ‘absolute sustainable lightweight design,’ additional strategies need to be activated to improve sustainability performance throughout the product’s life cycle. These may include electrifying the powertrain or

implementing closed-loop material or component systems to increase resource efficiency and reduce GHG emissions.

4. Conclusion & Outlook

Motivated by the research question of how lightweight design and the concept of absolute sustainability can be combined, the findings of this paper underscore the potential and limitations of coupling lightweight design with absolute sustainability. Based on the provided definition of absolute sustainable lightweight design, three sharing principles were chosen to assess the absolute environmental sustainability of five different BIW lightweight material concepts, thereby validating the proposed concept. The results indicate while lightweighting can reduce GHG emissions, none of the five BIW material concepts fully meet the criteria for absolute sustainability as all concepts exceeded the PB for CC within the AESE.

The concept still provides a lot of aspects to reinforce research in future work. We have only focused on the PB CC for three SoSOS scenarios, thus, other environmental (meaning other PB's) or socio-technical indicators (for determining the SoSOS with regard to the need for 'mobility') may matter for meticulously and critically analyzing the potential of lightweight design within absolute sustainable societies. Moreover, future work can analyze the combination of lightweight design with additional sustainability measures for vehicles, such as powertrain electrification in combination with the expansion of renewable energy systems, or evaluations on a circular economy scale.

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